Dosimetry with diamond detectors

G. Gervino[a], C. Marino[a], F. Silvestri[b], A. Lavagno[b], F. Truc[a]

[a]*Dipartimento di Fisica Sperimentale di Torino, via p. Giuria*
[b]*Dipartimento di Fisica, Politecnico di Torino*

Abstract

In this paper we present the dosimetry analysis in term of stability and repeatability of the signal and dose rate dependence of a synthetic single crystal diamond grows by Chemical Vapor Deposition (CVD) technique. The measurements carried out by 5 MeV X-ray photons beam show very promising results, even if the dose rate detector response points out that the charge trapping centers distribution is not uniform inside the crystal volume and this handicap, that affects the detectors performances, must be ascribed to the growing process. Synthetic single crystal diamonds could be a valuable alternative to air ionization chambers for quality beam control and for intensity modulated radiation therapy beams dosimetry.

Key words: dosimetry, X-rays, γ-rays, diamond
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1. Introduction

Diamond has a remarkable set of physical properties mainly due to the rigidity of its lattice and the relatively small mass of the carbon atom. The combination of these two structural aspects leads to the highest Debye temperature of any known material (2230°K), hence diamond detectors show a very high resistance to radiation damage and a very good temperature stability. Its electrical properties are determined largely by its band-gap of 5.45 eV, which is much larger than typical thermal energies at room temperature. The intrinsic material has a resistivity in the region $10^{13} - 10^{16}\Omega$ cm, making it, in electrical term, an insulator, although it is often referred to as a semiconductors like silicon and germanium. Diamond shows a very low leakage current and provides high signal-to-noise ratio when exposed to ionizing radiation. Other advantages are the high sensitivity and general stability of detector response and good time resolution. Natural diamond based devices are expensive. Recent developments of chemical vapor deposition (CVD) technique in fabricating synthetic single crystal diamonds deliver a promising issue for dosimetry applications due to its small size and fairly good tissue equivalence (atomic number Z=6, that is close to the average of human tissue).

2. Experimental

The synthetic single diamond crystal was grown by CVD technique adapting the fabrication process used for building heat spreader material employed in electronics and also infra-red transparent diamond windows for defense application. The synthetic diamond has the dimensions of 4.5 x 4.7 x 0.55 mm^3 and was polished on both faces. The crystal was equipped with evaporated Au electrical contacts 40 nm thick on both sides. Platinum wire were therefore bonded and finally the crystal was dipped in a coating resin to avoid any air ionization around the biased electrode. In order to investigate the defects left in the crystal by the growing process, thermo-stimulated current after 50 keV X-ray irradiation was measured by a Keythley 6517A and the results are presented in Fig. 1. We can see at around 255°C a current peak of small amplitude that reveals the low defects amount in the crystal. The crystal was irradiated several times by 5 MeV X-ray photons with a dose rate of 2 Sv/min. According with International Atomic Energy Agency (IAEA) requirements, the source-detector distance was fixed at 100 cm and a reference $10x10\text{cm}^2$ field was used. Fig. 2 shows the detector response shape under one of 5 MeV X-ray photons irradiation at the fixed dose rate of 2 Sv/min. The area under the detector current curve and both mean value and standard deviation were calculated. According with ref. [1] the stability is, for each irradiation, the percentage ratio of the standard deviation of the current ($sd_{current}$) to the mean value of the detector current ($mean_{Current}$, for sake of clarity we use the same symbols and definitions of ref. [1]):

$$stability = \frac{sd_{current}}{mean_{Current}} \times 100 \tag{1}$$

The synthetic crystal shows a stability of its response under irradiation around 8%. We can see in Fig. 2 the peak in the current response on the left edge of the graph, with the current slowing decreasing under the constant photons flux. The overestimation of the dose at the beginning of each irradiation that we observe has already been reported in ref. [2] for CVD diamond detector irradiated by ^{60}Co source, but it does not seem to have any influence on the measurement repeatability.

The repeatability, also called short term precision, is the percentage ratio of the standard deviation (sd_{Charge}) to the mean value of the collected charges for all the irradiation ($mean_{Charge}$):

$$repeatability = \frac{sd_{Charge}}{mean_{Charge}} \times 100$$

The repeatability between several irradiation was not so bad, around 2%.

3. Dosimetry

In order to study the dose rate response, the detector was irradiated by the 5 MeV photons beam varying the dose rate from 1 to 5 Sv/min. The dose rate D (in Sv/min) and the detector current I (nA) are linked by the relationship introduced by Fowler (see ref. [3]):

$$I = I_0 + A \times D^{\Delta}$$

Where I_0 is the dark current (in nA), A is the fitting free parameter and Δ is a parameter introduced in order to describe the deviation from linearity of the detector response. Δ value is predicted by phenomenological considerations (see ref. [3]) to be in the range $0.5 \div 1$, with $\Delta = 0.5$ for an ideal pure crystal without any traps or defects in the lattice and $\Delta = 1$ when a uniform trap distribution is present in all the crystal volume. Fig. 3 shows the detector current I (nA) as a function of the dose rate irradiation. The uncertainties are the standard deviations computed from different measurements taken in the same conditions. The reduced χ^2 of the fit is equal to 0.027.

Δ value evaluated fitting our experimental data is 0.84 ± 0.08: this value suggests that the traps distribution in the crystal lattice is not so uniform, and this can be ascribed to the growth process.

The Δ value of 0.84 is worse from the 0.98 found in natural diamond (see ref. [4]) and even worse of 0.97 ± 0.02 reported in ref. [1] for a synthetic CVD single crystal detector. The results of ref. [1] suggests that it is possible to improve the growing process as far as reaching the trap distribution uniformity of the best natural diamonds.

4. Conclusions

The goal of this research project was to investigate the performance of CVD synthetic single crystal diamond detectors built optimizing an already available industrial process devoted at present to the fabrication of heat spreader for electronics and infra-red transparent windows for defense applications. In this way we think it would be possible to produce synthetic diamond detectors at a lower price and so more accessible for many useful dosimetry applications. In particular, single crystals of synthetic diamond of small size and high sensitivity are very promising for intensity modulated radiation therapy beams dosimetry.

The thermo-stimulated current measurements reveal that a satisfactory low level amount of defects has been reached in the growing process, but on the other side, as the Δ value points out, trapping charge centers are distributed in a non-homogeneous way inside the crystal, much likely affecting the detector performances.

The stability results can be thought as an encouraging starting point that should be increased with further work as ref. [1] has demonstrated, the repeatability is acceptable and linearity of the detector response at the dose rate dependence is good.

References

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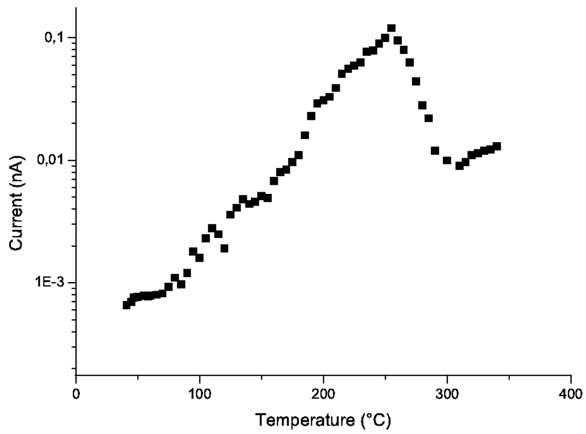

Figure 1: Thermo-stimulated current measurements done after 50 keV X-ray irradiation.

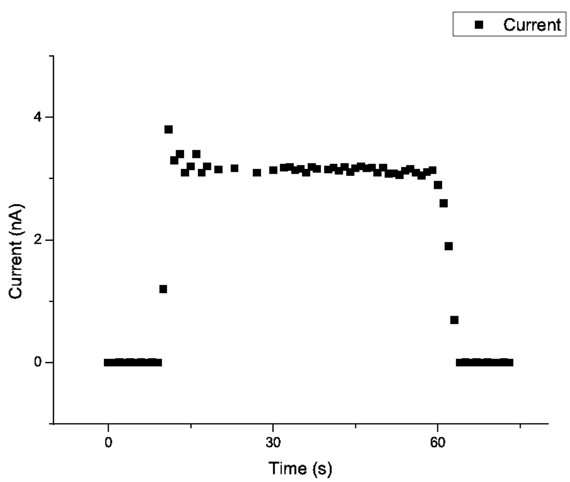

Figure 2: Current signal shape of the single crystal synthetic diamond under 5 MeV photons beam irradiation with a fixed dose of 2 Sv/min.

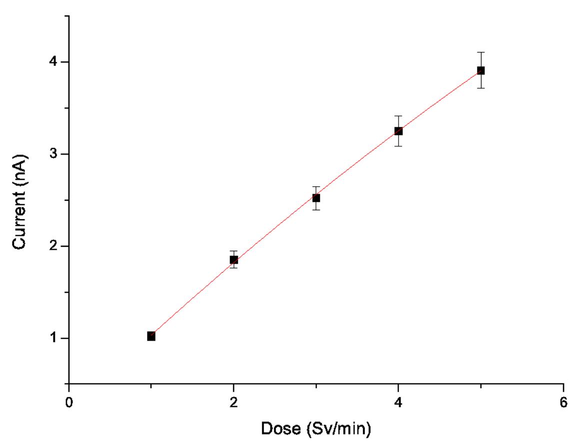

Figure 3: Induced current on the synthetic diamond vs dose rate.